Fermilab

Closeout Presentations

from the

Director's Preliminary Technical Review

of the

Proton Driver Project

March 15-17, 2005

Accelerator Physics Issues

March 15-17, 2005

J. Wei, G. Arduini, S. Henderson,

Baseline - 3 ms pulse length

– The baseline plan of a 3 ms macro-pulse length complicates the design in several aspects: possibly enhanced impact from Lorentz force and microphonics, possible deterioration of SRF cavity performance, enhanced foil scattering and radio-activation in the MI injection area, and more severe stripping foil heating.

→Comprehensively evaluate the risks associated with the baseline 3 ms pulse length operation.

MI driven specifications

- Tolerances on the linac RF control needs to be derived from the Main Injection requirements, along with chosen RF capture schemes in the Main Injector and compensation schemes in the 8 GeV transport. Performance of the fast ferrite shifters needs to be evaluated accordingly taking into account practical conditions including beam loading, static and dynamic errors in the reference line and the cavity phase and amplitude. … also, the linac phase error can compromise the performance of the passive de-buncher in the

→Identify Main Injector requirements in both transverse emittance and momentum spread, and guide the linac design.

Linac FODO vs. doublet

– We encourage continued optimization of the linac structure considering cost effectiveness and beam-dynamics performance. For example, the SNS linac uses quadrupoles doublets, extending the length of cryostats between the magnets to save cost while avoiding exceeding 90 degree phase advance envelope instability limit.

→

Linac end-to-end simulation

– Linac beam dynamics simulations up to this point have focused on ideal cases, generally with a small number of macroparticles, and with idealized input distributions. It is important to incorporate real anticipated errors in order to estimate realistic emittance growth, halo development, output energy jitter and energy spread. In particular, the specifications for the pulse-to-pulse or within-a-pulse RF amplitude and phase stability should be obtained from such simulations. Similarly, such simulations should explore the implications of correlated vs. un-correlated cavity phase and field errors.

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Off-normal condition

– Among existing proton and H- linacs, significant emittance growth (typically a factor of 10) is often observed. … For the proposed 8 GeV linac, which has 10 times the energy of the existing LANL linac with added complexity of SRF cavity forces, such growth is certainly possible. A significant growth in transverse emittance can possibly make the momentum collimation in the transport dysfunctional, enhance stripping foil scattering and activation, and complicate transverse painting. A fall-back scenario needs to be explored.

→Perform linac end-to-end beam-dynamics simulations including anticipated errors from RF control and magnet setpoints, and using a realistic front-end beam distribution; evaluate linac and transport performance under both normal and off-normal conditions

Black-body stripping

– We applaud focused efforts addressing stripping issues associated with the H-/H0 beams. The excessive radio-activation caused by the black-body radiation needs to be addressed. <u>We encourage detailed performance and cost evaluation of the mitigation plans.</u>

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Collimation, stability, diagnostics

– Transverse and momentum collimation based on stripping foils developed for the 8 GeV transport line provide halo cleaning down to 3 times rms beam size. This demands a good control of the beam trajectory along the line up to the injection area in order to minimize intensity fluctuations, unwanted losses, and injection efficiency reduction. The requirements on the ripple of the power supplies should be quantified. The collimation efficiency also depends on the accuracy of the optics of the line. Beam diagnostics requirements (number, type and performance of the monitors) both for the beam position and the profile measurements should be defined.

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MI RF capture

– <u>The RF capture scheme needs to be finalized as soon as possible.</u> With the adiabatic capture scheme, a carefully comparison with existing machines is needed to understand the expected beam loss. A potential problem could be the onset of microwave instability as a result of the micro-bunched, low-longitudinal emittance beam from the linac. <u>The “tightness” of the barrier bucket</u> ... Experimental proof … Leakage of beam to the abort gap might require envisaging transverse “cleaning” by means of the transverse feedback used as an exciter at low energy. Chopping at 53 MHz in the front-end and synchronous injection into waiting buckets may provide a cleaner solution. With this scheme, early R&D is needed for a chopper of fast rise/fall time (The original SNS MEBT chopper design has a rise/fall time specification of 2 ns.).

→Decide on the Main Injector longitudinal beam-capture scheme, and follow on the necessary R&D.

MI beam-dynamics survey

– A comprehensive survey is urgently needed on the Main Injector to understand the limiting physical aperture, the major existing and expected impedance sources, the expected beam loss distribution, and the intensity limiting mechanisms. Based on expected physical aperture and painted beam emittance, the collimation system can be designed and its efficiency evaluated, thus obtaining a credible ring activation map. Such aperture guidance is also needed for the design of new ring components and for impedance calculations.

→Systematically survey the existing and expected aperture of the Main Injector, and guide the design of collimation system and other components.

MI injection

– The proposed Main Injection H- injection needs to be optimized. Several aspects need attention: (a) In the absence of a dc chicane, the stripping foil #1 resides in a fringe field of a pulsing magnets, thus compromising H0 stripping goal; (b) The appearance of paining bump kicker #2 in the H- channel demands corresponding compensating kickers in the transport, making the beam spot on the foil potentially non-static both horizontally and vertically; (c) Particles stripped in foil #1 and #2 follow different orbits due to non-zero field; (d) The lattice quadrupole Q102 resides on the injection beam passage, thus lattice tuning may change beam orbits in both the circulating and the injection dump channels; (e) The injection septum does not seem to carry adequate clearance that allow efficient beam collimation; (f) Kicker #1 may mechanically interfere with the injection septum; and, (g) Operational robustness needs to be assessed with the practical operation of multiple dynamic kickers considering factors like phase advance in the transport, kicker programming and power supply matching, and injection dump channel arrangements.

→Optimize the Main Injector injection under practical constraints.

MI transition jump

– Transition jump with minimal perturbation to the ring lattice (first-order matched jump) is essential in ensuring high-intensity, low-loss operation. Locations need to be identified for the placement of the hardware.

→Identify and reserve space to implement the transition jump scheme.

MI electron cloud

- <u>Electron cloud effects limit beam intensity in many similar rings.</u> <u>Mitigation at a later stage is often complicated.</u> The large bunch intensity, the tight bunch spacing and the large number of bunches may lead to beam-induced electron multipacting and an electron cloud may build up along the bunch train as already observed in other machines (RHIC, SPS). Electron cloud effects (vacuum rises, beam instabilities) can limit the intensity of the beam in the SPS, demanding the use of e.g. transverse feedback. We strongly suggest the project team to investigate the problem for the new intensity regime, possibly starting with the computer codes available at BNL, CERN, LBL, etc.

→ Investigate the condition of observing the electron-cloud effects in the Main Injector

MI tracking

– A comprehensive computer simulation is needed for the ring covering the time of at least the injection painting and initial ramping and preferably transition crossing, including space charge and main coupling impedances.

→

H-, H+, e

– Simultaneous acceleration of H-, proton, and electron beams is likely to cause complications in several aspects including beam diagnostics and orbit control.

→

SC Cavities and Cryomodules

Findings

- The superconducting linac will accelerate the proton beam from 15 MeV to 8 GeV
  - 15 to 33 MeV: 1-spoke, β=0.21, 325 MHz
  - 33 to 110 MeV: 2-spoke, β=0.40, 325 MHz
  - 110 to 400MeV: 3-spoke, β=0.61, 325 MHz
    or elliptical β=0.47 and 0.61, 1300 MHz
  - 400 to 1200 MeV: elliptical β=0.81, 1300 MHz
  - 1200 to 8000 MeV: elliptical β=1, 1300 MHz

- RF pulses: 4.2 msec at 2.5 Hz
  1.4 msec at 10 Hz

Comments

- The important question of availability/reliability was not a prominent topic of discussion in this review. Related to this, the design gradient for the 1300-MHz cavities is 26 MV/m, which is approximately the best average gradient that has been demonstrated in the TTF cryomodules. To avoid having poor reliability in an accelerator system with many cavities and associated components, it will be necessary to compensate for system faults that can shut off a cavity or cryomodule, so-called single point failures. One way to provide this compensation is to design with extra margin in the gradient so that, after a fault, the cavities in operation can provide a higher accelerating gradient to restore the correct final beam energy. This flexibility to reset parameters after a fault is a major advantage of the superconducting accelerator. However, there appears to be no such margin provided in the present design.

- In order to reduce the number of klystrons (and therefore the cost) 36 cavities are driven by each klystron. This may have implications on the difficulty of providing field control in the cavities and on the availability of the proton driver. The total cost of the cryomodules is $101M while the cost of the klystrons+modulators+pulse transformers is $20.8M. Would the small cost increase resulting from reducing the number of cavities per klystron be offset by increased availability and easier field control?

- The rf power configuration in the front end does not allow controlling the fields in the superconducting cavities in the absence of beam loading. This could have implications on the commissioning of the facility. Separating the RT rf and the SC rf should be investigated.

- The transition between the RT linac and the SC linac takes place at 15 MeV. The pros and cons of transitions at lower energies have been investigated from the beam dynamics point of view. This should be balanced against the benefit of testing a superconducting section with beam as soon as possible.

- In the 3-spoke option, the assumed performance for the superconducting cavities (Epeak of 32 MV/m for the spoke cavities and 52 MV/m for the β=1 and 0.81 elliptical cavities) is challenging but not unrealistic. It may be optimistic for the β=0.47 and 0.61 elliptical cavities in the elliptical option.

- The β=0.61, 325 MHz spoke cavity is very close to the β=0.61, 345 MHz developed by ANL. The β=0.47 and (to a lesser degree) the 0.61, 1300 MHz elliptical cavities have not been developed and are quite different from any elliptical cavity developed so far.

- A detailed beam dynamics design was presented for the spoke cavity option in the medium velocity region. The same thing should be done for the elliptical cavity option.

- A process and a set of criteria by which the two medium velocity options will be assessed and a choice made needs to be developed.

- The single-pole model for the dynamic Lorentz detuning is not realistic and not supported by experiments, and would be even less valid for the long pulse length of 4.5 msec.

- The concept for the spoke cavity cryomodule has the power coupler entering from the top. The risk of contamination, together with the high assumed surface electric fields, may warrant relocating the couplers sideways or under the cavities.

- The schedule for the implementation of the SMTF is optimistic but its timely availability is crucial for the demonstration of key components of the Proton Driver.

Recommendations

- Specify the reliability/availability requirements for the overall PD accelerator system and for each subsystem. Decide what kind of margin is necessary in the design parameters, especially the design gradient of the 1300 MHz system, to provide the flexibility that is needed to compensate for single point failures.

- Rethink the rf power configuration and assess different options:
    - Separate rf for RT and SC
    - Fewer cavities per klystron

- Develop an integrated plan to demonstrate a superconducting section with beam as soon as possible.

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4.0 RF Power

The proposal for the rf power section has been worked out in great detail based on J-PARC and TESLA technology. The new element introduced is the high power phase shifter (and IQ modulator) which is essential to the proposed concept of driving many cavities with one klystron while permitting individual cavity field control.

Modulators

- Findings

- Controls and Interlocks of FNAL modulator and klystron at TTF II are mixed and separated into many small blocks. A new design has been proposed.

- Comments:
  - Concept for scaling of modulators from pulse length from 1.7ms to 4.5ms appears plausible but demonstration is necessary to verify that there are not hidden engineering problems.
- Recommendation:
  - Build and operate modulators with a pulse length of 4.5ms
  - Separate modulator and klystron controls and interlocks and upgrade technology to compact and modular design

Klystron and RF Feed

- Findings:

- Operating warm and cold section in Front End from the same klystron appears to be an operational headache.

- Comments:
  - TTF experience shows that Waveguide lengths has typically errors of +-30 degrees and loaded Q of the cavities with fixed coupler has errors of +-20%. With more effort one might get down to half of the phase error. This uncertaintanty must be accounted for.
  - Loss of any klystron will cause downtime of accelerator. This is expected to be a rare event due to the long lifetime of the klystron of about 100,000 hours.
  - TTF requires SF6 for waveguide operation at 5MW (in the narrow waveguide section of the circulator) despite much larger theoretical power handling capability
- Recommendation:

- Design klystrons installations for short time to repair.
- Demonstrate klystron operation at 5 MW without SF_6.
- Plan for separate klystrons for the warm and cold section in the Front End.

RF Phase Shifter R&D

- Findings:
  - Development plan appears reasonable. Several options are proposed.
- Comments:
- Recommendation:
  - Build IQ modulator with the phase shifter for 325 MHz and 1300 MHz and demonstrate phase and power control in A0 with sc. cavity at nominal power level.

LLRF and SCRF Instrumentation

- Findings:
  - Plan is to follow resonance frequency change of the cavity due to Lorentz force detuning during beam operation.
  - Amplitude and phase stability requirements of +-0.5 deg. and 0.5 % appear to be rough estimates rather then being backed up by solid simulations. Requirements could be ok based on studies done for RIA and SNS but may need some more thor-ough studies especially for worst case scenario. Should dis-tinguish between correlated and uncorrelated errors and include transverse focussing effects.
- Comments:
  - Lorentz Force detuning for long pulses (4.5ms) will be quite different from that of the TESLA pulse length (1.3ms). The

peak detuning is expected to increase significantly and since the main mechanical resonance is around 230 Hz will cover almost a full period of the mechanical resonance. The lower repetition rate may reduce the detuning but the likelyhood of being a subharmonic of the resonance frequency is increased. Also at TTF a variation of 50% in Lorentzforce detuning has been observed.

- Recommendation:
  - Maintain constant cavity frequency during flat-top (while beam is on) with piezo tuner.
  - Develop precise error budget for amplitude and phase stability requirements (correlated and uncorrelated, short- and long-term). Study also robustness of rf control against parameters variations (ex. beam current and gradient) and exceptions (ex. cavity quench).
  - Piezo tuners are required for Lorentz force compensation.

- Develop exception handling procedures
- Integrate beam based feedbacks with LLRF design
- Develop concept for commissioning procedures to identify LLRF and beam diagnostics needed for commissioning.

325 MHz IQ Modulators

- Findings:
  - Concept is ok, design expecting power test soon.

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10.1. Achieve Performance Goals a) Risks and Mitigation

- Findings:
  - Risk areas are
    - Fast IQ Modulators (ferrite phase shifters) since rf control performance will depend on phase and amplitude control range, response time and reliability of these devices.
      => Verify performance of IQ Modulators for 325 MHz and 1300 MHz with nominal rf power.

- RF control stability may not be guaranteed for large parameters variations such as beam current, beam phase and gradient.
  => Develop control algorithm adequate for large parameters variations and appropriate exception handling.
- Loss of cavity or klystron leads to beam loss.
  => Adequate procedures for cavity detuning and klystron replacement must be developed to minimize downtime in such a case.
- Operation of cavities at 25 MV/m. For Operation at 25 MV/m cavities should be guaranteed to operate higher (ex. 30 MV/m) which has not yet been demonstrated for a large number of cavities with beam.
  => Expect demonstration of cavity operation of 8 cavities in cryomodule at 35 MV at TTF within next year.

Linac Front End

P. Emma, S. Henderson, T. Wangler

(Proton Driver Review - March 16, 2005)

Findings:

- The Linac Front End is designed to accelerate multi-MW H^- ion beams to 400 MeV for injection into the 8-GeV Proton Driver linac The system consists of:
  - Ion Source [65 keV]
  - Radiofrequency Quadrupole (RFQ) [3 MeV]
  - Medium Energy Beam Transport (MEBT)
  - Room Temp. Triple Spoke Resonators (RT-TSR) [15 MeV]
  - Superconducting Single, Double and Triple Spoke Resonator sections, SSR [33 MeV], DSR [110 MeV], TSR [400 MeV].

- No design criteria were stated for emittance or beam loss, but it can be assumed at this stage that these criteria are similar to those of the SNS linac.

- The H^- ion source will be based on the existing SNS source, and the RFQ will be based on the existing J-PARC and SNS RFQs. The spoke resonator development is well advanced, and designs for the PD will be based on the RIA design, for which prototypes have already been built and successfully tested (see K. Shepard presentation) at a frequency of 345 MHz, near to that of the PD. All this suggests low to moderate technical risk and reasonably accurate costing.

Comments:

- The work presented appears to be quite thorough and of very high quality. We thank the speakers and their colleagues.

- We recognize the concentrated effort to use validated and existing designs and encourage this approach to mitigate risk.

- The design appears to be well founded for this level of the concept development. No high risk issues were identified, with the possible exception of the high-frequency chopper.

- No information was given as to trajectory correction, BPMs, and other beam diagnostics. This may be consistent with the present design level, but we are interested to see the diagnostics and corrections integrated into the design from the start, rather than added later.

- The SC-solenoid in the RT-TSR section introduces a mixed technology which caused some concern, but may be necessary.

- The strong solenoids in the RT-TSR may be difficult to align

- Development of a high-frequency chopper, required to make use of synchronous injection into the MI, is a technically challenging endeavor and represents risk adding complication to the front-end systems.

- Spoke resonators have had no beam tests yet, but SMTF will address this

- Are there ideas yet on initial machine commissioning, such as RF phasing, beam matching, and energy measurement, or is this considered straight forward?

- A room-temperature triple-spoke resonator section from 3 to 15 MeV was proposed for the first section after the RFQ. This concept uses 21 different cavities and the beam dynamics constrains the gradients to relatively low values (0.75 MV/m to 1.6 MV/m). This section is proposed as a room-temperature copper system. Although there is no reason that this will not work, this choice means that in the present design concept, superconducting resonators do not appear until 15 MeV; the first superconducting section goes from 15 to 33 MeV. From the point of view of obtaining early tests of the superconducting cavities in the SMTF, it would be desirable to reduce the warm to cold threshold energy. There is no reason why superconducting cavities cannot be used for energies below 15 MeV, but this would require prototyping additional superconducting spoke resonators. Therefore, there is a tradeoff between developing more low-beta superconducting resonators, allowing for earlier SMTF tests with superconducting cavities, versus using copper cavities for this section, which eliminates the prototyping required for superconducting cavities.

- Characterization of beam quality and twiss parameters of the linac input beam is essential for understanding downstream observations of accelerated beam. The committee encourages reserving adequate space in the MEBT for such diagnostics, for example inline emittance measurements and transverse and longitudinal beam profiles.

- A realistic input beam distribution is needed for simulations of realistic halo development and emittance growth. The committee encourages using one of the input distributions derived from existing ion source output emittance measurements for this purpose.

- It may become important to implement a halo collimation system in the MEBT. The committee encourages reserving space for collimating absorbers in the MEBT.

Recommendations:

- We suggest using 2 klystrons in the front end to separate the RF controls between the warm and cold RF sections

- Since it is important to obtain results at the SMTF for the superconducting spoke-cavity system as early as possible, it is desirable from that point of view to reduce the warm-to-cold transition energy to below 15 MeV. The designers should try to develop any options that would allow using superconducting cavities below 15 MeV, and compare these options with the present room temperature design. Possibly this can move the SC-solenoid back into a SCRF section.

- Incorporate low-energy collimation capability into the Front-End design, either as adjustable collimators in the MEBT, or included in the design of the room-temperature section.

- Reserve adequate space in the MEBT for inline beam diagnostics to allow full characterization of linac input beam quality and beam parameters.

6.0 Cryogenics

Findings

The PD CHL provides 4.5 K 2 phase refrigeration to the 325 MHz Linac and 1.9 K super fluid to the 1300 MHz Linac. Each can be independently cooled down and is feed by an independent transfer line. The 4.5 K transfer line runs the length of the 325 MHz Linac with each Cryomodule having a parallel cryogenic feed, while the 1.9 K transfer line connects only into the low energy end of the 1300 MHz Linac, using the internal "TESLA" distribution system. The 1300 MHz Linac is planned to be broken into five Cryo Units with nine or less Cryomodules each.

In addition to the PD CHL there are three other potential refrigeration efforts:

1) Meson Refrigeration: This system has produced in access of 1 kW at 4.5 K. Two Kinney vacuum pumps are being added to produce 60 W at 1.9 K, primarily for the ILC effort. Additional refrigeration will be required in ~2009.
2) New-Muon Refrigerator: The backup plan is to procure a new 300W 2K refrigerator for the ILC efforts and install it in the New-Muon building.
3) MTF Refrigeration: The magnet test 2K system will be used for cavity vertical dewar testing.

Comments

The CHL is being located at the 325 / 1300 MHz (4.5 / 1.9 K) transition, which minimizes the transfer line costs.

The current CHL capacity (1.5 x 1.3 x heat load estimate) is appropriate for this stage of the design.

Due to the 3 to 4 year lead time for medium to large refrigerators; refrigerators are critical path items.

Recommendations

1) Adding full vacuum pump flow purification to the MTF should be considered since the vertical dewar testing will produce a large amount of contamination.

2) The 1300 MHz Linac system segmentation needs to be optimized from a stand point of availability, repair times, number of thermal cycles, etc.

7.0 Civil Construction (P. Martin, E. Temple)

Findings

- The conceptual design is well advanced for this stage of the project.
- Frequent meetings with technical personnel are held to refine requirements.

Comments

- The cost estimate methodology is good. Comparisons to similar projects support the estimate.
- Most of the complicated construction regions have similarities to other recent projects.
- The MI-10 region is recognized as one of the most complicated, and is being studied.
- The biggest concern to the reviewers is the unknowns. For example, the number and location of emergencies exits, plans of utilization other than providing beam to the Main Injector (providing stubs to facilitate future extensions), etc. The largest impact on the design effort would be any change in location following an Environmental Assessment.

Recommendations

- Continue the design effort, especially in the MI-10 region.
- Explore what modifications to the civil design would facilitate future utilization most cost-effectively.

8.0 Main Injector Upgrades, Transfer Line, H- Stripping and Radiation Calculations

S. Henderson (ORNL) G. Arduini (CERN), P. Martin, J. Wei (BNL)

8.1 Transfer Line and Injection

Findings

Technical challenges associated with 8 GeV H- transport and stripping are well considered for this stage of the conceptual design. Identification of a new H- stripping mechanism arising from blackbody radiation, is an important development.

The transfer line optics design looks reasonable. Six collimator pairs are provided for transverse collimation. High dispersion regions are provided for momentum collimation.

Stripping due to blackbody radiation, the dominant source of beam loss in the transport line, results in substantial activation of the transfer line beampipe and high contact dose rates. A beam tube liner that lowers the temperature is one mitigation option.

A layout of the injection region was presented, showing only 135 mm separation between the injected and circulating beams at the downstream end of MI quad 101. This is inadequate.

Injection losses on the foil, and foil heating are a problem under the 270-turn injection (3-msec pulse length.).

Comments

While injection-related issues for the 1-msec long beam pulse envisioned in the upgrade plan for the Proton Driver look relatively straightforward, those same issues may in fact become limitations in the initial implementation requiring 3-msec accumulation time in the MI.

The peak foil temperatures are expected to reach 2500 K, similar to expected temperatures at SNS, but unlike SNS or PSR operation the MI foil will cool between beam pulses which could conceivably lead to shorter lifetimes due to fatigue. Little is known about foil failure mechanisms so scaling from foils subject to vastly different beam conditions may be problematic.

The high foil hits from circulating beam increases the local losses in the injection region, as well as distributed, uncontrolled, losses in the rest of the machine. The high dose rates in the injection region for 270 turn accumulation have important operational consequences: i) frequent replacement of nearby quadrupole coils may be necessary, and ii) the foil mounting and changing mechanism which will require routine handling in a region of the beamline with residual activation levels in excess of 1 R/hr. Handling of activated components in residual radiation fields of this magnitude require special handling provisions, built into the design from the beginning.

The operation of the MI with a 3-msec accumulation time represents substantial risk, relative to operation with a shorter accumulation time. The committee encourages further optimization of the linac pulse length in light not only of RF system cost reduction, but of reducing risk to achieving the PD performance goals for both the linac and the MI.

Some halo will not be intercepted by the transfer line collimation system, and that halo may be transported to and subsequently miss the foil. These "foil misses" can be subsequently stripped in the tertiary stripper foil, but these particles are bent in the opposite direction in the intervening magnets, and therefore lie on a trajectory which is different from that of the neutral hydrogen trajectory. A careful analysis of the anticipated inefficiency of the halo collimation system is needed in order to estimate the fraction of beam which misses the stripper foil. The injection dump line needs to be designed taking these different sources into account.

Requirements for the injection dump power handling capability should include foil misses, tolerances for beam trajectory control and sufficient margin to allow continued operation of the Proton Driver as the stripping efficiency is reduced due to gradual foil degradation.

The momentum collimation appears to work well for the design emittances, but will be less effective if the linac emittances growth is much larger than anticipated. Full end-to-end simulations, including all anticipated errors, are needed in order to full assess the requirements and capabilities of the halo and momentum collimation systems.

Many details of the transfer line were not presented, such as: how beam is switched between the linac dump and the transfer line, beam optics in the linac dump line, possible branch points for other utilization of the 8 GeV beam, beam instrumentation, and so on.

The clearance problem at MI quadrupole 101 needs to be addressed. The existing quad at that location is a (rolled) quadrupole with a half-dimension of approximately 8 inches. A special quad for this location could solve the problem at some substantial cost (taking saturation into account since the magnetic field has to track the other MI quads) but that cost is not yet included in the cost estimate.

Careful consideration of MI aperture is essential at this point, as clearance needs to be reserved for misalignments, orbit errors, halo growth, collimation, etc. A thorough analysis of MI aperture, particularly in the injection region needs to be performed (see Accelerator Physics section).

The nominal PD beam has a large stored energy (200 kJ at 8 GeV and 3 MJ at 120 GeV). A solution for the protection of the transfer line based on fast beam loss monitors and control of the power converter output and settings has been proposed. The number and type of beam loss monitors needs to be specified. At present no upgrade for the Main Injector machine protection system has been proposed (e.g. fast beam loss monitors, etc.).

Recommendations

1. Re-examine the injection region layout, incorporating information on existing magnet dimensions, both interior and exterior, and verify a feasible design.
2. Evaluate the collimation inefficiency and estimate the fractional “foil misses” that result.
3. Design the injection region and injection dump transport line to accommodate beam particles that miss the foil.
4. Do a preliminary design and cost estimate for a beamtube liner.
5. Conduct a one-day mini-review of the transfer line and MI injection.
6. Revisit the injection dump power handling capability taking into account foil misses and reserving margin for foil degradation.
7. Further optimize the linac pulse length in light not only of RF system cost reduction, but of reducing risk to achieving the PD performance goals for both the Linac and the Main Injector.

8.2 Radiation Calculations

Findings

The implications of beam loss have been evaluated with respect to several regulatory aspects, including radiation levels on the surface, groundwater activation, and air activation. Activation of components has also been examined, both from the standpoint of residual activation during accesses, and, in less detail, damage to materials.

Comments

The air activation calculations identified carbon-11 and nitrogen-13 as the major isotopes of concern, and concluded a 2-hour delay prior to making an access was sufficient.

Low-conductivity water (LCW) activation has not been addressed.

The conclusion that “ …no radiation related problems are expected” is not justified at this point in the design. Numerous problems are expected, some easier to solve than others, but each will require consideration, and in some cases, costs that have not yet been assigned.

The beam dump absorber of the Main Injector is designed to accept 3.26×10^{18} p/year @ 150 GeV. This is only about 1 % of the integrated intensity that the PD is expected to deliver. As a result, more shielding might be necessary. It is not clear if the present core and the vacuum window can tolerate the nominal beam intensity at 120 GeV.

The losses occurring in the transfer line due to blackbody radiation stripping will activate the vacuum chamber. The estimated residual radiation can reach 1000 mrem/h. A method of confining the losses in localized areas by proper collimation should be studied further.

Recommendations

1. Include argon-41 in the air activation calculations. Its longer decay time may require longer waits before accesses are allowed.
2. Examine LCW activation and assess whether it poses a problem for service-building accessibility during operations. Determine which components might need closed-loop systems to mitigate any radiation problems in the service buildings.

8.3 **Main Injector Upgrades**

Findings

A program of MI upgrades was presented including large-aperture quadrupoles for the extraction regions, RF upgrades to handle higher beam currents, power supply upgrades to reduce the cycle time, collimators, and a gamma-t jump system.

The dual-PA upgrade to the Main Injector (MI) RF System is not capable of supporting a beam intensity of 1.5×10^{14} which will be delivered by the Proton Driver. The installation of new RF system is necessary for accelerating the nominal intensity. A design for a new MI RF system that meets the requirements for the Proton Driver was presented.

MI beam dynamics at the intensities expected with the Proton Driver have been examined.

Comments

Of the upgrades listed above, the large-aperture quads, collimators, and gamma-t jump system will be fabricated, installed and commissioned prior to the PD. One of the RF upgrades – installing two additional cavities and a second power amplifier on each existing cavity – is also funded.

The power supply system upgrades for shorter cycle times, and the RF upgrade which fabricates and installs new 53 MHz RF cavities, will occur over a longer time scale.

More needs to be learned about collective effects in the MI at full Proton Driver intensities to give confidence in high intensity operation. Impedance estimates based on possible MI configurations in the PD era should be obtained and used as inputs. Any relevant beam studies that can explore higher single-bunch intensities should be pursued. Measurement aimed at establishing damper system requirements at PD intensities should be performed. Full 3D space-charge simulations should proceed.

The gamma-t system will be critical for high-intensity operations. At the present time, it is thought that only seven of the eight subsets of the system can be installed due to conflicts with other devices.

Recommendations:

1. Continue analysis of collective effects, both during injection and at full intensity, including impedance and stability estimation, establishing damper system requirements, and analyzing space-charge driven halo development.
2. Evaluate the adequacy of a gamma-t jump system with only a partial implementation of the original design.
3. Pursue beam studies in the MI to explore to the extent possible, beam parameters nearer the PD intensity, as well as to confirm assumptions about impedances and to validate calculational tools.

9.0 COST

All costs were presented as FY04$. Base costs were estimated for both M&S (materials and supplies) and SWF (labor/effort salaries, wages and fringes). Overheads were then put into the estimate at 16.05% for M&S and 30.35% for SWF.

9.1 Linac

Findings

- A total cost estimate for the linac including overheads and a 30% contingency of $497M was presented.
- The Proton Driver Linac design concept is based on experience at currently operating accelerators or test facilities. Therefore, there is a good cost basis for much of the proposed machine. A partial list of systems and experience is:

System	**Experience Base**
Ion Source	SNS, DESY, & others
RFQ	JHF (KEK) & SNS
Spoke Resonators	RIA (ANL) & LANL
Beta < 1 Elliptical Cavities	SNS (JLAB) & RIA (MSU)
Beta = 1 Elliptical Cavities	TESLA Collaboration
RF Power Supplies (Modulators & Klystrons) & Distribution	TTF, FNAL SNS, vendors
Fast Ferrite Phase Shifters	FNAL & ANL Prototypes Only

- Two key areas where development is required are the fast phase shifters and long pulse (4.5 ms) klystrons at both 325 MHz and 1300 MHz. Engineering estimates for production quantities of phase shifters, and single-unit vendor pricing for Klystrons have been used.
- The Cryomodules at $101.6M are the largest cost component in the project. The estimate for production versions of the PD cavities and cryomodules comprise
    - M&S costs ($86.7M)
        - Based on budgetary quotes from vendors (55%) - for example for processed cavities, vendor communications, TESLA/SNS costs and Engineering Estimates
    - EDIA (Design Phase) Costs ($3.3M) based on an estimated 500 drawings / CM x 20 hrs / drawing (CMS, LHC experience at FNAL)
    - An assembly ($10.7M) at Fermilab model based on Engineering estimates for each step
- It was clearly stated what had been EXCLUDED from the estimate.
    - Costs of physicists and scientific staff were not included.
    - The estimate does not include costs of any required Main Injector Upgrades

    - R&D and prototyping costs are excluded, although higher unit costs for "first production items" are assumed.
    - The existence of an SMTF (Superconducting Module Test Facility) was assumed and no costs were included in the estimate. Thus costs for the creation of a facility for assembling the PD CMs are not included.
    - Disclaimers for Cryomodule Assembly at Fermilab
        - No rework/fix/modify inefficiencies estimated at this time.
        - No worker/tech/tooling inefficiencies estimated at this time ("6-6.5 h work out of 8 hours paid" effect for techs)
- Civil Construction, at $81M, is the second largest element of the cost estimate.
    - The Conventional Facilities group (Dixon Bogert supported by FESS [Facilities and Engineering Support Section] personnel) have been holding weekly meetings to develop the requirements for this area of the Proton Driver.
    - The PD site placing the linac inside the Tevatron ring has been chosen and a design concept has been developed for a 700m long linac and 972m long Transport Line both based on a cut and cover enclosure and supporting surface buildings including a full length klystron gallery.
    - A 20 drawing set displays the design concept for the PD Civil Construction.
    - FESS has prepared a cost estimate by doing quantity "take offs" and applying unit costs based on Fermilab experience (as far back as the Main Injector where the Civil Construction was quite comparable) and current versions of standard handbooks for costs of civil construction.
- The basis of estimate for instrumentation was least well developed. Here allowances in the estimate were made based on Fermilab experience.

Comments

- A rather impressive "bottoms up" style estimate has been prepared at this design concept stage.
- The proposed Beta=1 Cryomodule (CM) cost of ~$1.5M / CM are so comparable to those for TESLA at 1.05 MEuros / CM (~$1.5M / CM).
- The design costs of $3.3M for the CM M&S cost of $86.7M seem quite low.
- We do not comment on the adequacy of a 30% contingency. Although we do note that this is at a very early stage of project development where significant contingencies of even 50% or more are appropriate.

Recommendations

- Continue detailed development of project plans, schedules, and estimates as planned.
- Consider developing and preparing a formal Proton Driver R&D Plan with an associated detailed schedule and cost estimate.

- Work with the Proton Plan team to develop an optimized program for the Plan. Consider developing and preparing a formal Main Injector Upgrade Project with an associated TDR, detailed cost and schedule.

9.2 Synchrotron

Findings

- A total cost estimate for the synchrotron including overheads and a 30% contingency of $384M was presented.
- See the first finding in Section 9.3 for a description of how the estimate was put together.

Comments

- Less effort was put into developing a detailed "bottoms up" style estimate for the synchrotron than for the linac. Sometimes an insufficiently developed estimate results in an underestimate.

Recommendations

- If proceeding with the Synchrotron option is seriously considered by management, a more rigorous cost estimate should be assembled as soon as possible.

9.3 Comparison of Linac and Synchroton Concept Cost Estimates

Findings

- The goal of the PD team was to provide a "fair and consistent" cost comparison between the Linac and Synchrotron PD options. To do this the persons responsible for assembling the estimate have tried to
    - Keep independent of technical or physics related issues
    - Develop a consistent level of estimation and detail for each option
        - Use the same labor rates, $/sf for buildings and data format / cost rollup
    - Assemble a reasonable level of back up documentation (Basis of Estimate) for both cost estimates
    - Understand the "Range of Values" for the cost of a PD
- The Proton Driver Project Engineer presented a set of observations based on his working with the two proponent teams to put "comparable" estimates together that result in a cost range for the Linac of $348M to $487M and for the Synchrotron of $285M to $396M.
- A cost difference of about $100M was noted.

Comments

- The Committee did not review these cost estimates in detail (nor are they really ready for detailed scrutiny); however, we find that, based on comparison with similar projects elsewhere, the cost estimates seem to be in a reasonable range. The conclusion that the linac might cost on the order of $100M more than the synchrotron appears plausible.

Recommendations

- None

EXECUTIVE SUMMARY

The Proton Driver Team presented a design concept for an 8 GeV super-conducing proton linac. This proposed accelerator would deliver 0.5 MW (upgradeable to 2 MW) of beam power at 8 GeV, and enable the delivery of 2 MW or more from the Main Injector at up to 120 GeV. This would enable a diverse physics program, including precision neutrino oscillation and neutrino scattering measurements, study of rare decays of muons, kaons, and other particles, and possibly non-HEP experiments. The design work and preliminary R&D presented was quite impressive for a project at this very early stage. In most cases the designs presented are conservative and are based closely on existing designs from other projects. The key risks have been identified, and the proponents are working on developing an R&D plan to address them. Overall, the Committee found that the linac design concept is credible and appears capable of achieving the performance goals. While much work still needs to be done to develop the design concepts to the level required for a real construction proposal, the Proton Driver team is to be congratulated on the nice work done so far.

An alternate design for a rapid cycling 8 GeV synchrotron, which can also deliver enough beam to enable 2 MW from the Main Injector, was also summarized. This option is less flexible and less capable than the linac version. However, it is gratifying to see that a number of ideas developed in studying this option are being implemented as part of the Proton Plan to increase beam intensity in the near future.

This review concentrated on technical considerations, but looked briefly at a rough cost comparison that was presented between the linac and synchrotron options. Schedule and program management were not reviewed. The charge to the Committee is attached.

TECHNICAL ISSUES

The Committee believes that while the design concepts are fundamentally sound, much work remains to be done, and many comments and recommendations for improvement are included in this report. The key technical issues are summarized here.

<u>SCRF</u>

The combination of copper spoke, and superconducting spoke and elliptical cavity resonators seems to be a good approach, and an appropriate R&D program for testing each of the key cavity designs first individually on test stands and then with beam has been proposed. Most of the cavity designs are direct copies of or closely based on existing designs from other projects. However, the Committee is concerned that the gradient assumed for the elliptical cavities is near the current state of the art and suggests that designing for a modestly lower gradient could reduce risk, particularly if this project wants to be on a fast track. The RF input couplers are also a risk, since their required performance for the 2 MW upgrade are at or beyond the current state of the art.

Radio Frequency Systems

The RF system design proposed feeds 36 cavities from a single klystron. This concept requires fast phase shifters to control individual cavity amplitude and phase. Experience at Fermilab and other labs and R&D efforts here have already demonstrated the feasibility of the fast phase shifter concept, but additional work is required to demonstrate that robust devices that meet all of the performance specifications can be made. Since these are key to the economical RF distribution system, the R&D on these should be a top priority. The capability of the klystrons to provide 4.5 msec pulses also is still to be demonstrated for both the 325 MHz JPARC and 1300 MHz TESLA models. The proposed Superconducting Module and Test Facility (SMTF) will provide a key facility for the R&D on the Proton Driver RF cavities and power systems.

Main Injector Upgrades

Several improvements of Main Injector performance will be implemented as part of the on-going Proton Plan that will increase the number of protons on target (POT) for NuMI over the next several years. Substantial additional upgrades will be required to permit the MI to accept and accelerate the much more intense beam from the Proton Driver, and work on this has only begun. The H- injection scheme needs further study to ensure its viability. The 270 turn injection in the baseline phase of the linac make this problem more difficult. Another key set of questions are to understand the potential limitations on beam intensity in the MI (e.g. electron cloud effect, or single or multibunch instabilities) and how to mitigate them.

Cryogenics and Civil Construction

The cryogenic system and the civil construction appear to be straightforward. Both are conservatively designed, and build on a wealth of experience. The risks here are low.

COST

Cost estimates for both the Linac and Synchrotron Proton Driver design concepts were presented. The two estimates were put together by different sets of people at different times, with somewhat different assumptions. The linac estimate is the better developed of the two. An effort has been made by the Proton Driver team to put these on a common basis to facilitate a comparison, but differences remain. The linac was found to be modestly more costly than the synchrotron - $498M versus $384M, including all indirect costs plus a nominal 30% contingency. The Committee did not review these cost estimates in detail (nor are they really ready for detailed scrutiny); however, we find that, based on comparison with similar projects elsewhere, the cost estimates seem to be in a reasonable range. The conclusion that the linac might cost on the order of $100M more than the synchrotron appears plausible. The Proton Driver team should be commended for making a serious attempt to estimate the costs at this early stage.

RESPONSE TO CHARGE QUESTIONS

The Charge to the Committee asks several specific questions, to which we respond briefly here. Further details can be found in the main body of this Report.

- Is it the committee's judgment that the established performance goals can be achieved based on the superconducting linac design implementation?

The superconducting linac design presented appears to be capable of achieving the goals of 0.5 MW beam power delivered at 8 GeV. However, less work has been done to demonstrate that the Main Injector upgrades will make it capable of capturing and accelerating this intense beam to deliver the goal of at least 2 MW at 120 GeV.

  – What are the primary performance risk elements within the linac concept and are they adequately mitigated at this stage of the concept development?

The primary risks are the fast phase modulators and their use to control individual cavity phases and amplitudes, the long pulse length in the 0.5 MW baseline configuration, the load on the RF input couplers in the 2 MW upgrade, and achieving 26 MV/m accelerating gradient in the production beta = 1 cryomodules. There are obvious mitigation strategies for all of these, either through focused R&D which is under way (e.g. on the fast phase modulators), or modest design modifications (e.g. increasing the number of klystrons in the initial configuration).

  – Are the Main Injector requirements understood and adequately addressed within the upgrade concept?

The Main Injector requirements are reasonably well understood, but work has only begun on developing the design the concepts that will address these challenging requirements.

  – Does the committee have any suggestions to offer that could improve the soundness of the design concepts?

Yes, and these are included in the text of the report.

- Are the relative cost estimates of the linac-based and synchrotron-based implementation credible (at the 25% level)?

The conclusion that the linac might cost on the order of $100M more than the synchrotron appears plausible. A more detailed cost estimate and a more focussed cost review would be required to firmly establish the cost difference at the 25% level.

- Is the R&D program effectively targeting the primary technical and cost issues?

For the linac, yes. In particular, the early R&D on the fast phase shifters is already under way. Tests of modulators and klystrons at pulse widths up to 4.5 msec are planned for the coming year. The SMTF program will be a particularly important vehicle for pushing the R&D on the superconducting RF system. Further thought needs to be given as to how to develop the key elements of the Main Injector upgrades.

- Does the linac implementation concept effectively extend the reach of the current program of intermediate term improvements to the existing Proton Source, i.e. the "Proton Plan"?

Yes. The Proton Driver concept seems to reliably extend the reach provided by the Proton Plan, and will enable an increase in beam intensity at 120 GeV a factor of four to five, and at 8 GeV by an order of magnitude or more beyond what can be delivered by the existing proton source with the Proton Plan. Most of the Main Injector upgrades planned under the Proton Plan will also be of benefit with the Proton Driver beam, for example the wider aperture quads and the γ_t-jump system.